The Use of Nanomaterials to Achieve NASA's Exploration Program Power Goals

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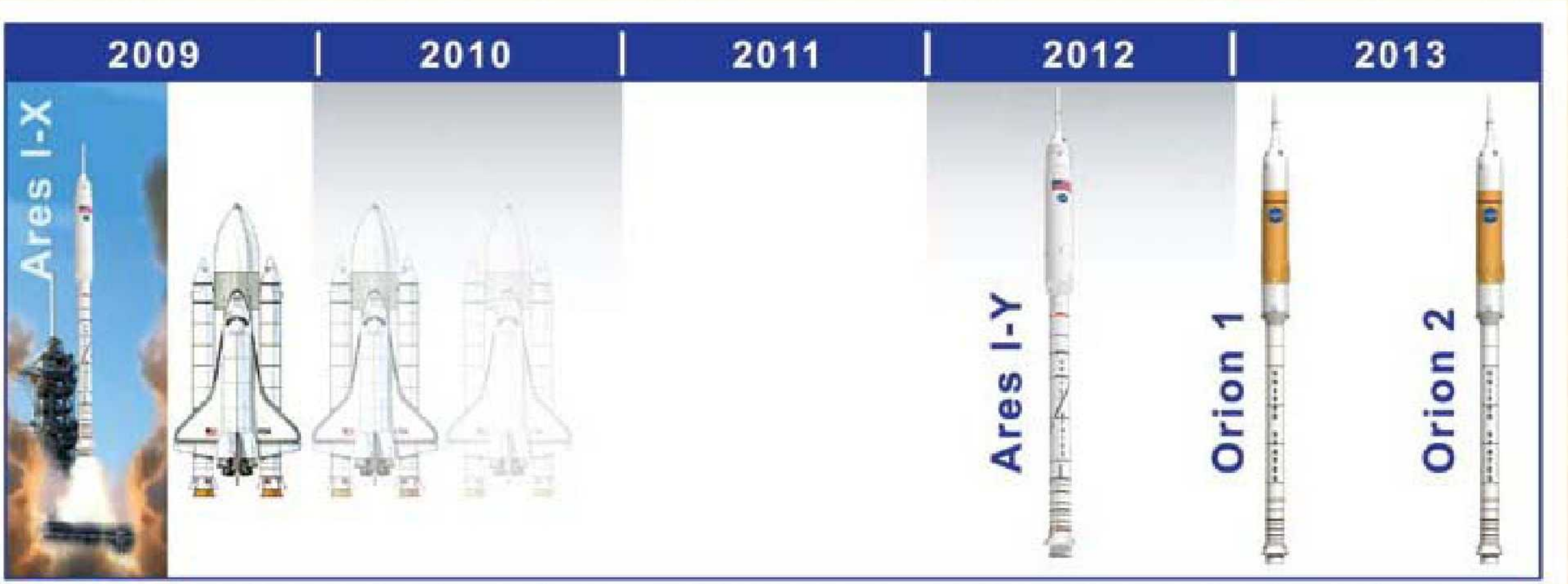
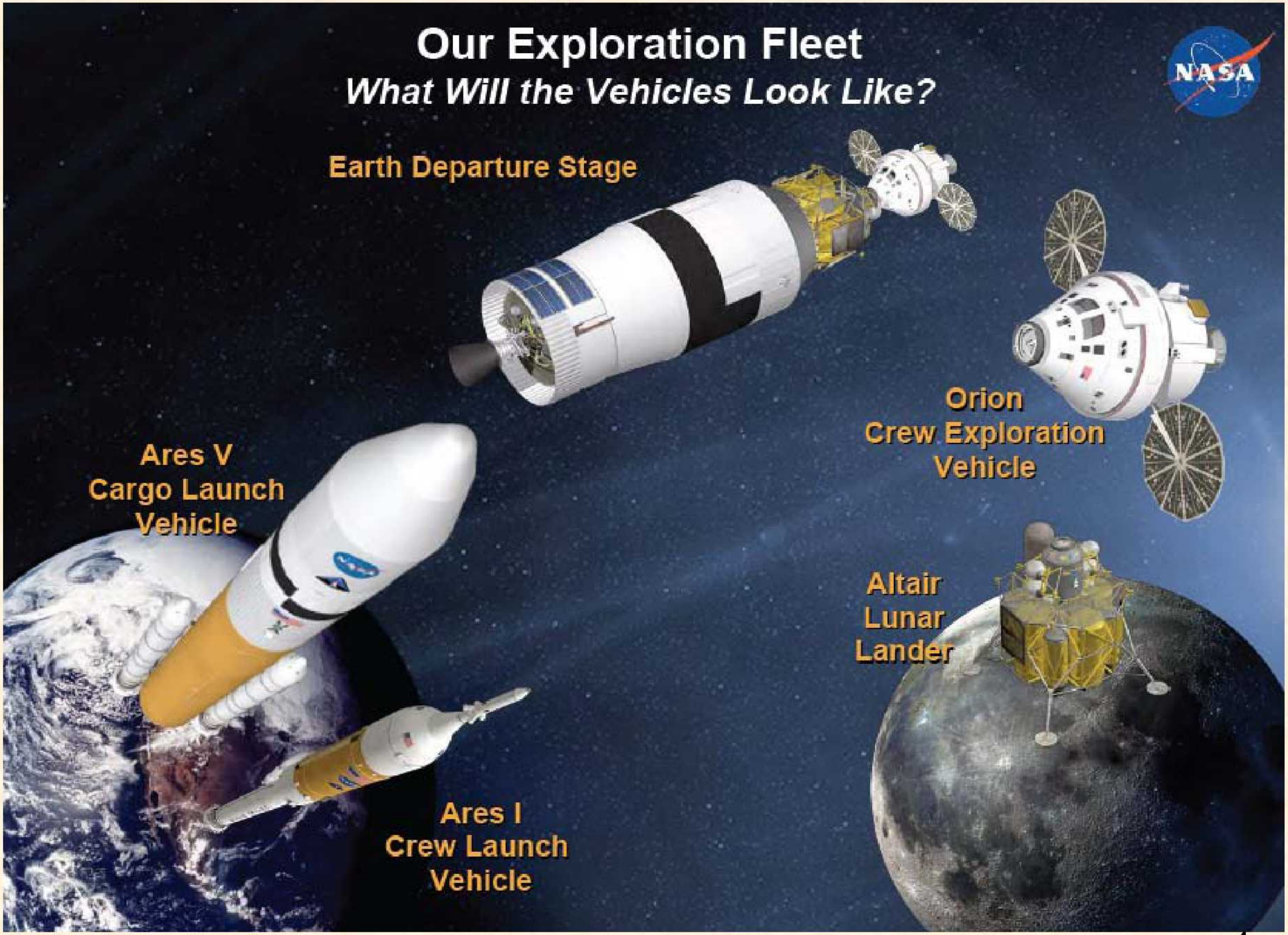
Outline

- Power Needs (Customers) for Exploration
- Technology Programs to Achieve Safe and High Energy Power Goals
- Summary and Conclusions

Exploration Program



Courtesy: NASA Ambassador package



Courtesy: NASA Ambassador package

Lunar Mobility

Lunar Surface Systems (Mobility)
Pressurized Rover

Preliminary Power Requirements:
Safe, reliable operation
 >150 Wh/kg at battery level
 ~ 500 cycles
Operation Temp: 0 to 30 C
Maintenance-free operation

Lunar Surface Systems (Mobility) / Lunar Outpost

Scenario-Based Planning:

Rechargeable batteries for mobility systems and/or portable utility pallet and/or power & support unit

Crew Mobility Chassis Specifications

- 969 kg dry vehicle mass
- >100 km range, upgradable with PUPs
- 0-5 kph low gear, 0-20 kph high gear
- 20 kWh onboard energy storage (Li-ion battery)
- 5.9 kW peak power, 1.15 kW average power and 125 W standby power.
- Nominal drive time is 87 hours and stand-by time is 800 hours.

Portable Utility Pallet

- Logistics: 25 kg Oxygen, 90 kg Water, 90 kg Wastewater
- Power Generation: 4.4-kW, 5.5-m diam Orion-class solar array
- Energy Storage: 10 kWh (Li-ion batteries)
- Mass: 708.9 kg (dry), 963.4 kg (wet)

Outpost Power Needs

- ~20-40 kW lunar daytime power level
- ~10-20 kW lunar nighttime power level
- Modular systems with 5-10 year calendar life
- Reliable, human-rated operation in thermal, dust, launch/landing, vacuum environments
- Low mass and volume
- Autonomous control and operation

Battery Needs

- 10-hour discharge and 10-hour charge
- 2000 discharge/recharge cycles
- Temperature controlled to 0 to +30 °C
- 5 year calendar life

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Altair Lunar Lander Ascent Module

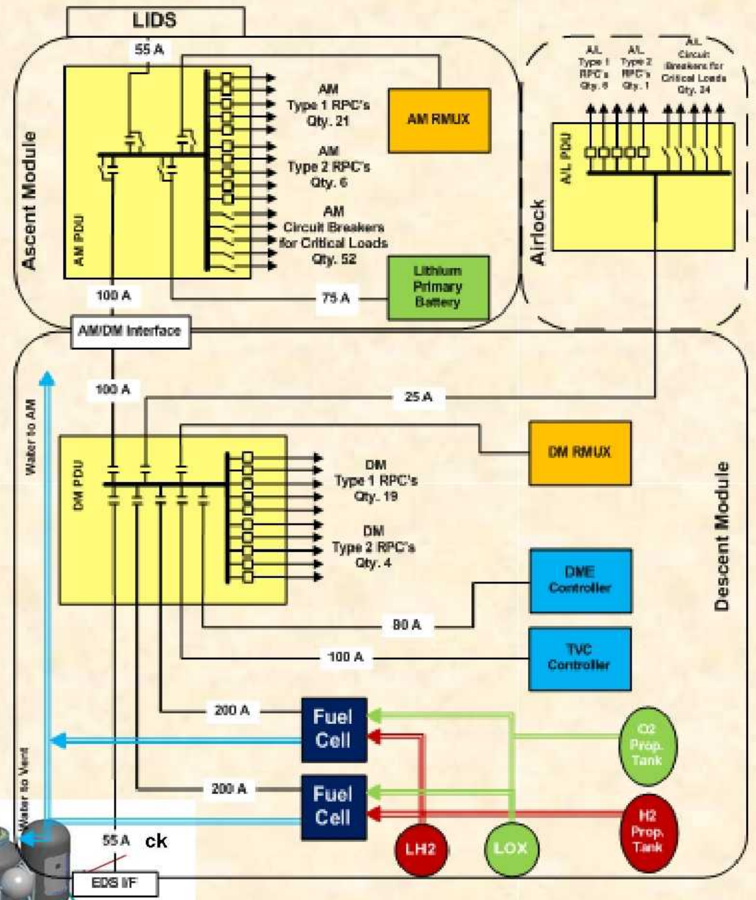
<u>Ascent Module:</u>

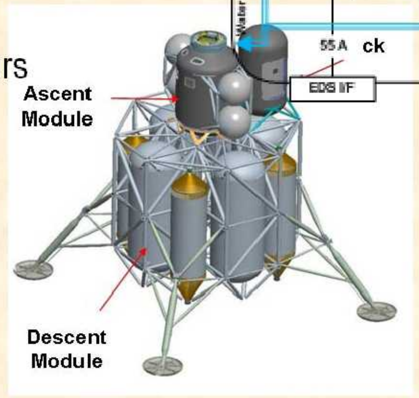
- Secondary Batteries are considered <u>critical</u> for the Ascent Stage.
- LDAC-3 recommended a 121.6 kg, 22.7 kW-hour primary battery, sized for an ascent underburn.
- Key risks associated with primary batteries:
  1. Inability to verify proper battery function in-flight before critical use;
  2. Probable large mass impact when peak/average power ratios defined;
  3. Altair need for power in excess of the 1500 W power transfer requirement from Orion & EDS identified in LDAC3
- Rechargeable batteries can eliminate these risks; but mass should not increase appreciably

– 160 – 200 W-hr/kg at the battery level may be sufficient.

– Nominally ten recharge cycles are required with 1.67 kW nominal power and 2 kW peak power, operating for 7 hours continuously.

– Human-safe operation from 0 to +30 °C and zero to 1g.





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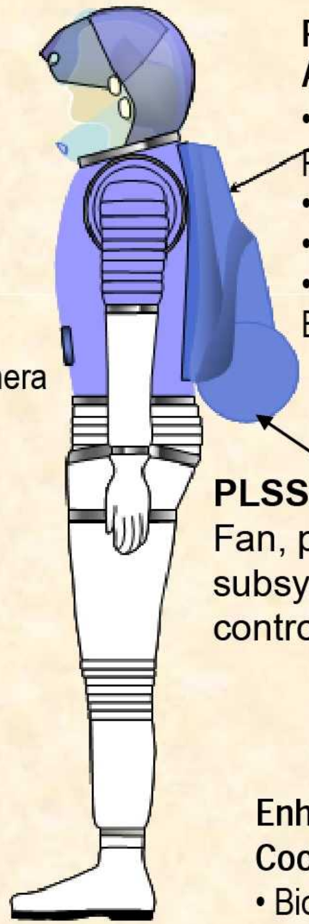
Extravehicular Activity (EVA) Suit
Lunar EVA 2nd Configuration

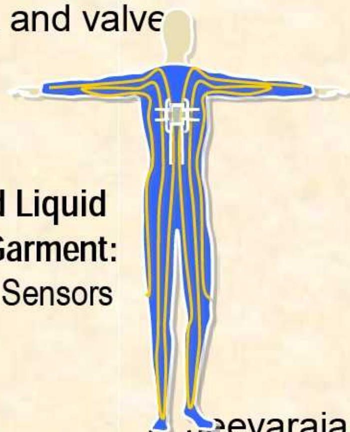
Enhanced Helmet Hardware:
- Lighting
- Heads-Up-Display
- Soft Upper Torso (SUT) Integrated Audio



Power / Communications, Avionics & Informatics (CAI):
- Cmd/Cntrl/Comm Info (C3I) Processing
- Expanded set of suit sensors
- Advanced Caution & Warning
- Displays and Productivity Enhancements

Video:
Suit Camera

PLSS:
Fan, pump, ventilation subsystem processor; Heater, controllers, and valve



Enhanced Liquid Cooling Garment:
- Bio-Med Sensors

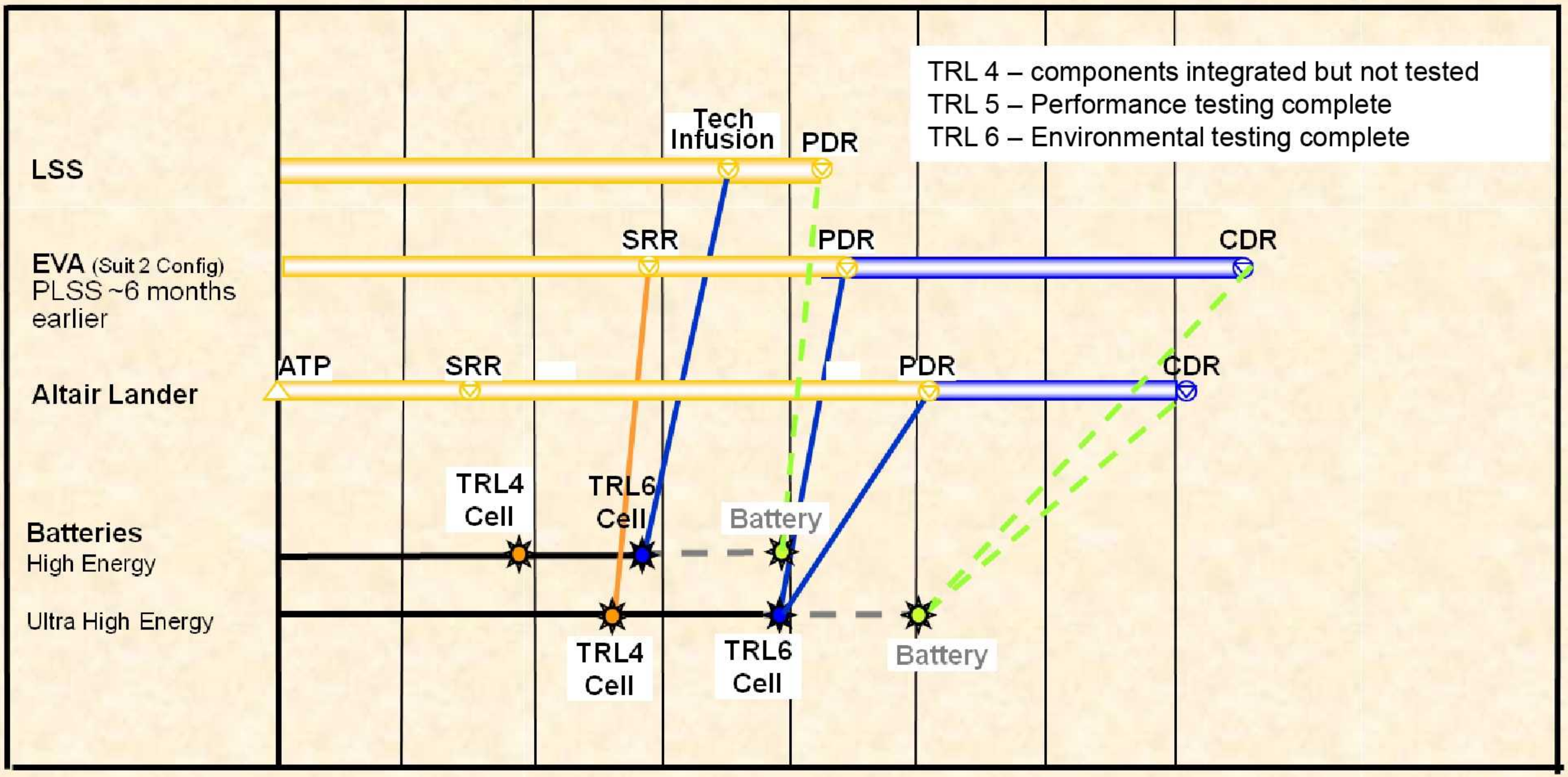
- Power to support 8-hour EVA provided by battery in Portable Life Support System
- Preliminary battery design goals:
  - Human-safe operation
  - 144 W (average) and 233 W (peak) power

    Assumes 1% connector loss and 30% margin for growth in power requirements
  - No more than 5 kg mass and 3 liter volume
  - 100 cycles (use every other day for 6 months)
  - 8-hour discharge to at most 85% depth-of-discharge
  - Temperature controlled to 0 to +30 °C
- Secondary batteries are considered critical for EVA Suit 2.

Current Suit Batteries:
EMU: 20.5 V; min 26.6 Ah (7 hr EVA), 9A peak, 5 yr, **<15.5 lbs**, 30 cycles
SAFER:42 V; 4.2 Ah (in emergency only)
REBA: 12.5 V, 15 Ah, (7 hr EVA); 5 yr, ~**6 lbs**
EHIP:6 V, 10.8 Ah; (7 hr EVA); 5 yr, ~**1.8 lbs**

Exploration Technology Development Program (ETDP)
Energy Storage Battery Development Schedule for Constellation

PDR: Preliminary Design Review
CDR: Critical Design Review
SRR: System Requirements Review
TRL: Technology Readiness Level



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Key Performance Parameters for Battery Technology Development

Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
Safe, reliable operation	No fire or flame	Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a moderate reduction in the performance with flame retardants and non-flammable electrolytes	Benign cell venting without fire or flame and reduce the likelihood and severity of a fire in the event of a thermal runaway	Tolerant to electrical and thermal abuse such as over-temperature, over-charge, reversal, and external short circuit with no fire or flame
Specific energy Lander: 150 – 210 Wh/kg 10 cycles Rover: 150 – 200 Wh/kg EVA: 200 – 300 Wh/kg 100 cycles	**Battery-level** specific energy*	90 Wh/kg at C/10 & 30 C 83 Wh/kg at C/10 & 0 C (MER rovers)	130 Wh/kg at C/10 & 30 C 120 Wh/kg at C/10 & 0 C	**135** Wh/kg at C/10 & 0 C "High-Energy"** **150** Wh/kg at C/10 & 0 C "Ultra-High Energy"**	**150** Wh/kg at C/10 & 0 C "High-Energy" **220** Wh/kg at C/10 & 0 C "Ultra-High Energy"
	Cell-level specific energy	130 Wh/kg at C/10 & 30 C 118 Wh/kg at C/10 & 0 C	150 Wh/kg at C/10 & 0°C	**165** Wh/kg at C/10 & 0 C "High-Energy" **180** Wh/kg at C/10 & 0 C "Ultra-High Energy"	**180** Wh/kg at C/10 & 0 C "High-Energy" **260** Wh/kg at C/10 & 0 C "Ultra-High Energy"
	Cathode-level specific capacity $Li(Li,NiMn)O_2$	140 – 150 mAh/g typical	$Li(Li_{0.17}Ni_{0.25}Mn_{0.58})O_2$: 240 mAh/g at C/10 & 25°C $Li(Li_{0.2}Ni_{0.13}Mn_{0.54}Co_{0.13})O_2$: 250 mAh/g at C/10 & 25°C 200 mAh/g at C/10 & 0°C	**260** mAh/g at C/10 & 0 C	**280** mAh/g at C/10 & 0 C
	Anode-level specific capacity	320 mAh/g (MCMB)	320 mAh/g MCMB 450 mAh/g Si composite	**600** mAh/g at C/10 & 0 C with Si composite	**1000** mAh/g at C/10 0 C with Si composite
Energy density Lander: 311 Wh/l Rover: TBD EVA: 240 – 400 Wh/l	**Battery-level** energy density	250 Wh/l	n/a	**270** Wh/l "High-Energy" **360** Wh/l "Ultra-High"	**320** Wh/l "High-Energy" **420** Wh/l "Ultra-High"
	Cell-level energy density	320 Wh/l	n/a	**385** Wh/l "High-Energy" **460** Wh/l "Ultra-High"	**390** Wh/l "High-Energy" **530** Wh/l "Ultra-High"
Operating environment 0°C to 30°C, Vacuum	Operating temperature	-20°C to +40°C	-50°C to +40°C	**0°C** to **30°C**	**0°C** to **30°C**

Assumes prismatic cell packaging for threshold values. Goal values include lightweight battery packaging.

* Battery values are assumed at 100% DOD, discharged at C/10 to 3.0 volts/cell, and at 0°C operating conditions

** "High-Energy" = Exploration Technology Development Program cathode with MCMB graphite anode

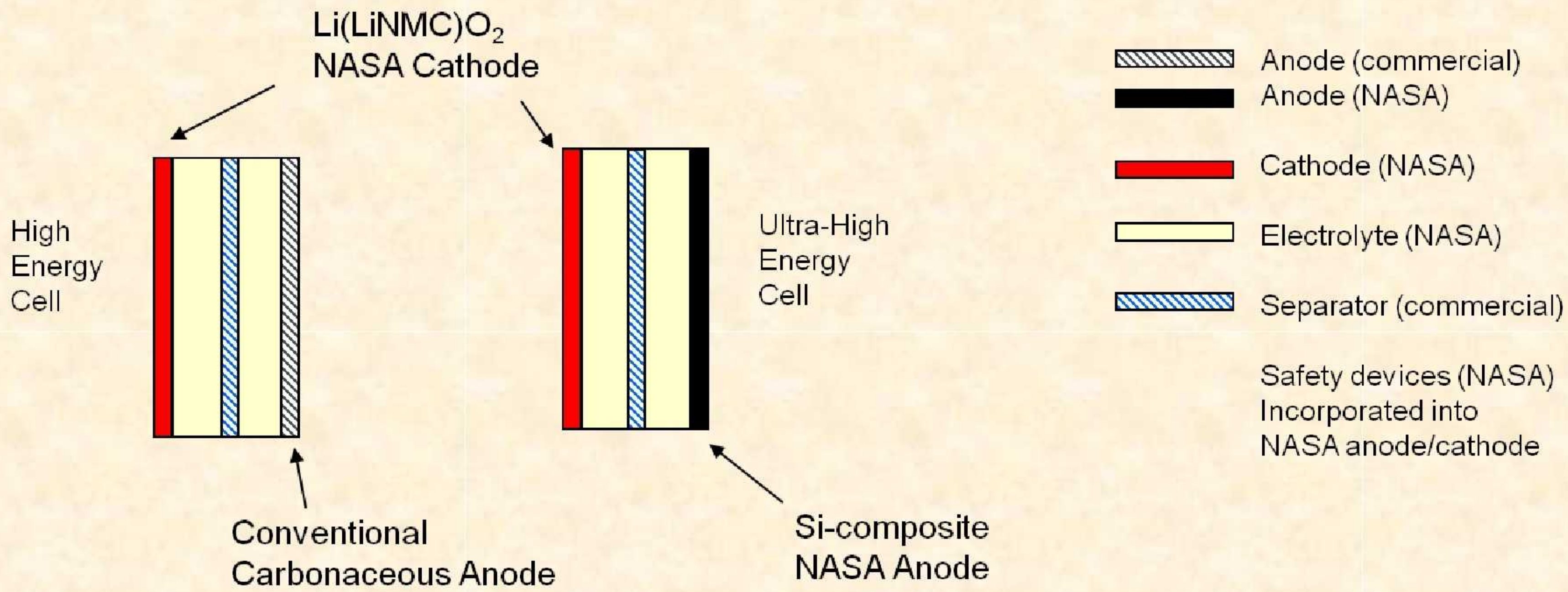
"Ultra-High Energy" = Exploration Technology Development Program cathode with Silicon composite anode

Revised 06/02/2008

ETDP Li-ion Cell Development

- **Component-level goals** are being addressed through a combination of NASA in-house materials development efforts, NASA Research Announcement contracts (NRA), and grants
- Materials developed will be delivered to NASA and screened for their electrochemical and thermal performance, and compatibility with other candidate cell components
- Other activities funded through NASA can be leveraged – NASA Small Business Innovative Research (SBIR) Program and Innovative Partnership Program (IPP)
- Leveraging off other government programs (DOD, DOE) for component-level technology
- Leveraging off other venues through Space Act Agreements (SAA) that involve partnerships with industry partners such as Exxon; non-profit organizations such as Underwriters Laboratory (UL), etc.

Energy Storage Project Cell Development for Batteries



<u>"High Energy" Cell</u>

Baseline for EVA and Rover

Lithiated-mixed-metal-oxide cathode / Graphite anode

Li(LiNMC)O_2 / Conventional carbonaceous anode

150 Wh/kg (100% DOD) @ battery-level 0^0C C/10

80% capacity retention at ~**2000** cycles

<u>"Ultra-High Energy" Cell</u>

Upgrade for EVA and Altair, possibly Rover

Lithiated-mixed-metal-oxide cathode / Silicon composite anode

Li(LiNMC)O_2 / silicon composite

220 Wh/kg (100% DOD) @ battery-level 0^0C C/10

80% capacity retention at ~**200** cycles

Anode Development
Led by NASA GRC (William Bennett, ASRC)

- **Goal:** 1000 mAh/g at C/10 (10 hour discharge rate) and 0°C
  - Over 3 times the capacity of SOA Li-ion anodes
  - Threshold value = 600 mAh/g at C/10 and 0°C

Technology Challenges	Current Approaches to Address
Minimize volume expansion during cycling	•Pursuing various approaches to optimize the anode structure to accommodate volume expansion of the silicon •Nanostructured Si composite absorbs strain, resists active particle isolation on cycling •Incorporation of elastic binders in Si –graphite and Si-C matrices •Improvement of mechanical integrity by fabricating structure to allow for elastic deformation
Minimize irreversible capacity loss	•Protection of active sites with functional binder additives •Pre-lithiation approaches are possible •Nanostructured Si resists fracture and surface renewal
250 cycles	Loss of contact with active particles reduces cycle life. Addressing volume changes and improvement of mechanical integrity will improve cycle life

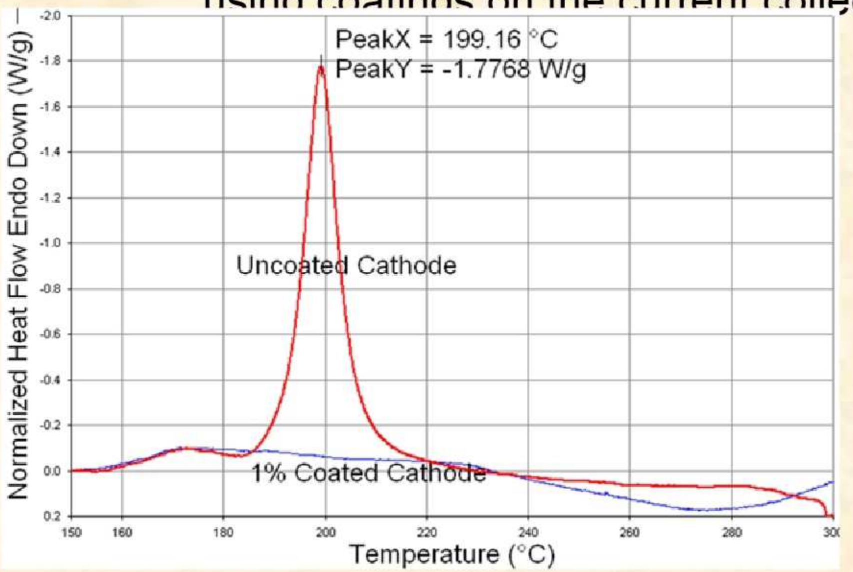
Cathode Development
Led by R. Bugga (JPL)

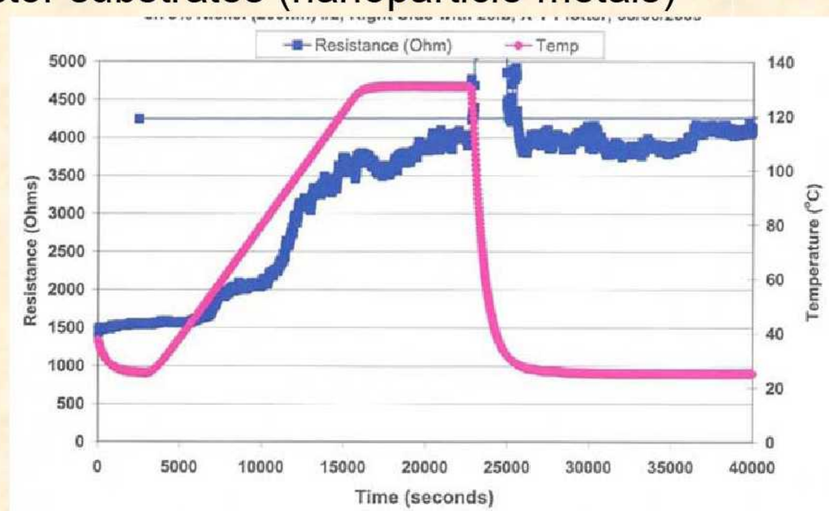
- **Goals:**
  - Specific capacity of 280 mAh/g at C/10 and 0°C to 3.0 V
  - High voltage operation to 4.8 V
  - Improved thermal stability over conventional Li-ion cathodes

Technology Challenges	Current Project Approaches to Address
High specific capacity at practical discharge rates	•Vary stoichiometry to determine optimum chemical formulation •Reduce particle size •Experiment with different synthesis methods to produce materials with physical properties such that their specific capacity is retained on production scale
Low volume per unit mass	•Vary cathode synthesis method to optimize properties that can: •Improve energy density •Improve ability to cast cathode powders •Facilitate incorporation of oxide coatings, which have the potential to increase rate capability and reduce capacity fade to extend cycle life
Minimize 1st cycle irreversible capacity loss and irreversible oxygen loss	•Surface modification via coatings to improve cathode-electrolyte interfacial properties •Improves capacity retention •Reduces capacity fade

Safety Component Development
Led by NASA JSC (Judy Jeevarajan)

- Development of internal cell materials (active or inactive) designed to improve the inherent safety of the cell
  - Approach 1: Develop a high-voltage stable (phosphate type) coating on cathode particles to increase the safe operating voltage of the cell and reduce the thermal dissipation by the use of a high-voltage stable coating material. (Nanosized material)
  - Approach 2: Develop a composite thermal switch to shutdown cell reactions safely using coatings on the current collector substrates (nanoparticle metals)





SBIR

Phase I:

TDA Research: Si/C composite anode (nanomaterials)

TH Chem: Improved cathodes – Polymer/S type

Phase II: Yardney Technical Products

- In Phase I, high-rate capability with Cu nanorod and Fe_3O_4 anodes was demonstrated.
- Phase II has several facets:
  - Baseline Li titanate anode (NTP) with $LiNiCoO_2$ cathode
  - High voltage cathode $LiCoPO_4$
  - Nanoengineered anode of Fe_3O_4 with Cu nanorods
  - Carbon nanotubes (CNT) with Al current collector and Fe_3O_4 anode
- 6 Other SBIR Phase I at other Centers
- **FY10:** Reviewed nanotechnology related proposals for both batteries and capacitors.

Summary

- Exciting Future Programs ahead for NASA
- Power is needed for all Exploration vehicles and for the missions.
- For long term missions as in Lunar and Mars programs, safe, high energy/ultra high energy batteries are required.
- Nanomaterial usage also increases the energy density of the cells apart from increasing the power density.

Acknowledgment

Coworkers in Power Systems Branch